AN ASSESSMENT OF THE HIGHWAY CAPACITY MANUAL EDITION 6 ROUNDABOUT CAPACITY MODEL

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ABSTRACT

In an earlier paper, the author presented an assessment of the roundabout capacity model given in the Highway Capacity Manual 2010 (HCM 2010) including discussions of lower capacity of roundabouts in the USA compared with Australian and UK roundabouts and the issue of possible increases in roundabout capacities in the USA over time due to changes in driver behavior. The latest HCM Edition 6 (TRB 2016) has introduced major changes to the roundabout capacity model parameters compared with those given in HCM 2010. This paper presents an assessment of the HCM Edition 6 model compared with the HCM 2010 model and the SIDRA Standard capacity model for roundabouts employed in the SIDRA INTERSECTION software which is widely used in US practice. In particular, the Environment Factor parameter used in the SIDRA Standard capacity model is discussed in relation to calibrating the model to match the capacity estimates from the HCM Edition 6 model. Comments are included on various aspects of the model discussed in HCM Edition 6, Chapter 22. Using a multilane roundabout example given in the HCM, capacity and the resulting degree of saturation (v/c ratio), delay, level of service and queue length estimates from the HCM Edition 6, HCM 2010 and the SIDRA Standard capacity models are compared.

INTRODUCTION

The latest Highway Capacity Manual Edition 6 ("*HCM 6*") *(1)* has introduced major changes to the roundabout capacity model parameters compared with those given in the Highway Capacity Manual 2010 ("*HCM 2010*") *(2)*. The models in these two editions of HCM are based on major roundabout capacity research projects in the USA as reported in the FHWA Report SA-15-070 *(3)* and NCHRP Report 572 *(4)*, respectively.

In an earlier paper, the author presented an assessment of the HCM 2010 roundabout capacity model including discussions of lower capacity of roundabouts in the USA compared with Australian and UK roundabouts and the issue of possible increases in roundabout capacities in the USA over time due to changes in driver behavior *(5)*. In a related paper *(6)*, the author discussed some common and differing aspects of three well-known analytical models of roundabout capacity, namely the HCM 2010 model, the Australian ("*SIDRA Standard"*) model *(7-16)* and the UK TRL (linear regression) model *(17-19)*.

In addition to the SIDRA Standard capacity model, the HCM 6 and HCM 2010 models are provided in the SIDRA INTERSECTION software (developed by the author) with various extensions. Some of these extensions and related issues were discussed in an earlier paper *(5)*.

HCM 6, Chapter 22 lists various limitations of the roundabout capacity model presented in this chapter and provides specific recommendations for the application of alternative tools to the analysis of roundabouts. This includes making adjustments to the parameters used in alternative models for matching the HCM capacity estimates. For such model calibration purposes, the SIDRA Standard capacity model uses an *Environment Factor* as a general parameter to allow for the effects of such factors as driver aggressiveness and alertness (driver response times), standard of intersection geometry, visibility, operating speeds, sizes of light and heavy vehicles, interference by pedestrians, standing vehicles, parking, buses stopping, and so on *when such factors are not modeled explicitly*.

The SIDRA Standard capacity model option in SIDRA INTERSECTION is based on research on Australian roundabouts *(5-9)* thus reflecting Australian traffic characteristics. The default value of the Environment Factor in the SIDRA Standard model was set to 1.2 for both one-lane and two-lane roundabouts to match the HCM 2010 capacity model estimates representing lower capacities of roundabouts in the USA compared with Australian roundabouts. The value of this parameter for Australian conditions is 1.0.

To match the estimates from the HCM 6 model, the default value of the Environment Factor in the SIDRA Standard model was set to **1.05** for one-lane roundabouts (both approach road and circulating road have one lane) and for mixed one and two-lane approach and circulating road arrangements (either approach road or circulating road has one lane). For two-lane roundabouts (both approach road and circulating road have two lanes), the default value of the Environment Factor was kept as **1.2** as in HCM 2010.

It should also be noted that, in a recent study, detailed calibration of the SIDRA Standard Model to match the capacities observed at roundabouts in Poland gave Environment Factors 1.05 for one-lane roundabouts and 1.39 for two-lane roundabouts *(20)*.

Discussion of the HCM 6 and HCM 2010 models, and the comparisons of the HCM 6, HCM 2010 and SIDRA Standard models are given in the next section. The model differences are further explored using the HCM 6, Chapter 33 multilane roundabout example.

Comments are included on various aspects of the roundabout capacity model discussed in HCM Edition 6, Chapter 22 with a view to possible future improvements to the model.

MODEL FEATURES AND COMPARISONS

HCM Edition 6 continues to describe the roundabout capacity model as "*procedure presented in this chapter incorporates a combination of simple, lane-based regression and gap-acceptance models for both single-lane and double-lane roundabouts.* " as in HCM 2010 *(1, 2)*. Thus, the model can be viewed both as an *empirical* (exponential regression) model and a *gap-acceptance* model. The basic model which is the same in HCM Edition 6 and HCM 2010 can be expressed as:

$$Q_g = f_{HVe}\, f_p\, A\, e^{-B\, q_m} \qquad (1)$$

where parameters A and B are related to follow-up headway and critical gap parameters:

$$A = 3600 / t_f \qquad \text{or} \qquad t_f = 3600 / A \qquad (2a)$$

$$B = (t_c - 0.5\, t_f) / 3600 \qquad \text{or} \qquad t_c = 3600\, B + 0.5\, t_f \qquad (2b)$$

and f_{HVe} = heavy vehicle (HV) factor for entry lane capacity, f_p = pedestrian factor for the effect of pedestrians crossing in front of entry lanes, q_m = opposing (conflicting) flow rate in pcu/h adjusted for heavy vehicles (this is normally the circulating flow rate in front of the subject lane but may include a percentage of exiting flow rate depending on user specifications), t_f = follow-up headway (s) and t_c = critical gap (s).

Fundamental aspects of the HCM 6 / HCM 2010 roundabout capacity model were discussed, particularly as a *lane-based model* in an earlier paper *(5)*. While the basic form of the roundabout capacity equation is the same in HCM Edition 6 and HCM 2010, the parameter values have changed significantly. They are summarized in *Table 1* where n_c = number of circulating lanes and n_e = number of entry lanes.

The capacity estimates from the HCM 6, HCM 2010 and SIDRA Standard capacity models are shown in *Figure 1* for single-lane roundabouts ($n_c = n_e = 1$) and for the dominant (right) and subdominant (left) lanes at two-lane roundabouts ($n_c = n_e = 2$).

The y intercept of the capacity equation represents the *roundabout saturation flow* as the highest capacity which is obtained at zero opposing flow, e.g. 1380 veh/h for single lane roundabouts as seen in *Table 1* (also see *Figure 1*). In gap-acceptance modeling, this is obtained from the follow-up headway, t_f as a saturation flow rate, $s = 3600 / t_f$. FHWA Report SA-15-070 *(3)* Chapter 5 on HCM 6 model development indicates that the regression model was obtained by fixing the y intercept to this saturation flow rate using observed follow-up headway values. *Entering flow normalized by t_f* shown in Figure 28 of the report is in fact the *proportion of time when gaps are available in the circulating stream* as discussed in an earlier paper by the author as an important aspect of gap acceptance modeling *(6)*. The method used in the development of the HCM 6 roundabout capacity model confirms the nature of the model as a "combined gap and empirical (regression)" model.

Table 1- Highway Capacity Manual roundabout capacity model parameters (A, B) and the corresponding gap acceptance parameters (t_f, t_c)

Model Parameters	A	B	t_f	t_c	t_f / t_c
Highway Capacity Manual Edition 6 *(1)*					
Single Lane Circulating (n_c = 1)					
Single Lane Entry (n_e = 1)	1380	0.00102	2.61	4.98	0.52
Multi-Lane Entry (n_e > 1) [Applies to all lanes]	1420	0.00091	2.54	4.54	0.56
Multi-Lane Circulating (n_c > 1)					
Single-Lane Entry (n_e = 1)	1420	0.00085	2.54	4.33	0.59
Multi-Lane Entry (n_e > 1)					
Dominant Lane (Right lane for US driving)	1420	0.00085	2.54	4.33	0.59
Subdominant Lane (Left lane for US driving)	1350	0.00092	2.67	4.65	0.57
Highway Capacity Manual 2010 *(2)*					
Single Lane Circulating (n_c = 1)					
Single Lane Entry (n_e = 1)	1130	0.00100	3.19	5.19	0.62
Multi-Lane Entry (n_e > 1) [Applies to all lanes]	1130	0.00100	3.19	5.19	0.62
Multi-Lane Circulating (n_c > 1)					
Single-Lane Entry (n_e = 1)	1130	0.00070	3.19	4.11	0.78
Multi-Lane Entry (n_e > 1)					
Dominant Lane (Right lane for US driving)	1130	0.00070	3.19	4.11	0.78
Subdominant Lane (Left lane for US driving)	1130	0.00075	3.19	4.29	0.74

n_e = number of entry lanes, n_c = number of circulating lanes.

The estimates from the SIDRA Standard model can vary according to additional parameters used in the model. The graphs in *Figure 1* were derived using the following default parameters:

- Roundabout geometry parameters (default values): Inscribed Diameter = 140 ft for one-lane roundabouts and 160 ft for two-lane roundabouts, Lane Width = 13 ft, Entry Radius = 65 ft, Entry Angle = 30 degrees.
- Environment Factor = 1.05 for one-lane roundabouts and 1.2 for two-lane roundabouts.
- Entry Flow / Circulating Flow Ratio: *No* adjustment for one-lane roundabouts and *Low* adjustment for two-lane roundabouts.
- Origin - Destination Factor accounting for unbalanced flow conditions: Medium effect with the factor decreasing from 1.00 at zero circulating flow to 0.7 - 0.8 at a high circulating flow rate of 1400 veh/h. This is determined in SIDRA INTERSECTION software as a function of the O-D flow pattern and amount of queuing on entry lanes using an iterative method. The values used for *Figure 1* are based on a simplified version of the method. Lower values of the Origin - Destination Factor indicate more unbalanced conditions and values less than 1.00 reduce the capacity.

The field data used in the development of the SIDRA Standard and HCM 6 roundabout capacity models are summarized in *Tables 2 and 3*. The differences in data can be used to explain the reasons for differences in capacity estimates from these models. In particular, the differences can be explained by significant differences in follow-up headway and critical gap values. This can be seen in *Tables 2 and 3* as well as *Figure 2* which shows the correlation between these two gap acceptance parameters.

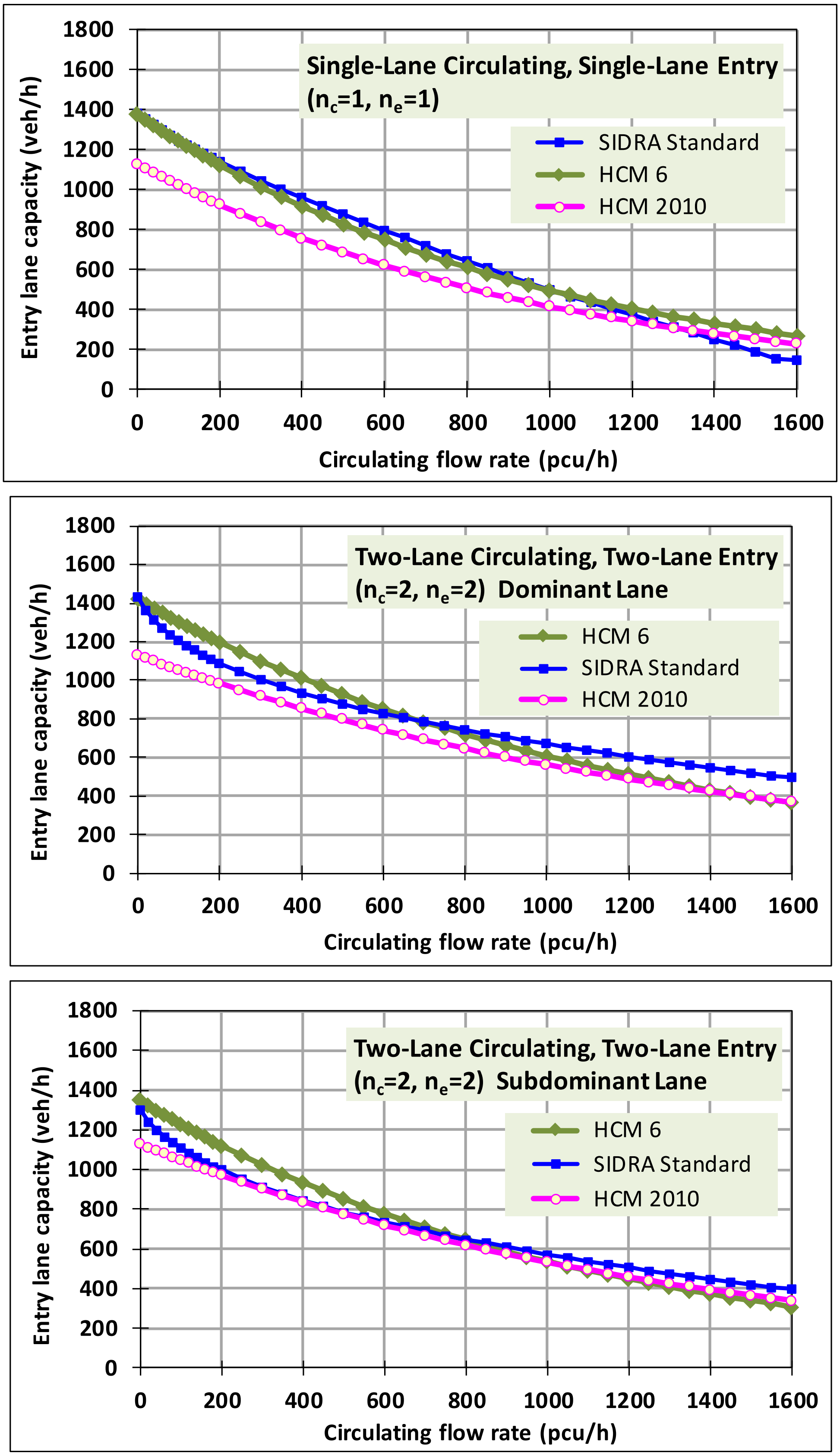

Figure 1 - Comparison of HCM 6, HCM 2010 and SIDRA Standard capacity models for one-lane and two-lane roundabouts

***Table 2 - Summary of survey data from roundabouts in Australia used for calibrating the SIDRA Standard roundabout capacity model** (7-9)*

	Total Entry Width (m)	No. of Entry Lanes	Average Entry Lane Width (m)	Circul. Width (m)	Inscribed Diameter (m)	Entry Radius (m)	Entry Angle (°)
Range	3.7 - 12.5	1 - 3	3.2 - 5.5	6.5 - 12.0	16 - 220	4 - ∞	0 - 80
Average	8.1	-	3.84	9.6	56	39.0	29
	Follow-up Headway, t_f (s)	Critical Gap, t_c (s)	Fol. Hdw / Crit. Gap Ratio, t_f / t_c	Circul. Flow (veh/h)	Total Entry Flow (veh/h)	Dominant Lane Flow (veh/h)	Subdom. Lane Flow (veh/h)
Range	0.80 - 3.55	1.90 - 7.40	0.29 - 0.92	225 - 2648	369 - 3342	274 - 2131	73 - 1211
Average	**2.04**	**3.45**	**0.61**				

Average values for	t_f	t_c	t_f / t_c
All data	2.06	3.45	0.60
Data for D_i = 16 - 30 m	2.27	4.08	0.56
Data for D_i = 31 - 50 m	2.24	3.46	0.65
Data for D_i = 51 - 65 m	2.02	3.29	0.62
Data for D_i = 66 - 100 m	1.52	2.74	0.55
Data for D_i = 101 - 220 m	1.76	3.14	0.56

D_i: Inscribed Diameter (reducing t_f an t_c values are seen with increasing roundabout size, D_i except for very large size, D_i = 101 - 220 m)

***Table 3 - Summary of survey data from roundabouts in the USA used for calibrating the HCM Edition 6 roundabout capacity model** (1, 3)*

	Total Entry Width (m)	No. of Entry Lanes	Average Entry Lane Width (m)	Circulat. Width (m)	Inscribed Diameter (m)	Entry Radius (m)	Entry Angle (°)
Range	NA	1 - 2	3.4 - 6.7*	NA	35 - 75*	NA	8 - 61*
Average	NA	-	NA	NA	NA	NA	NA
	Follow-up Headway, t_f (s)	Critical Gap t_c (s)	Fol. Hdw / Crit. Gap Ratio	Circul. Flow (veh/h)	Total Entry Flow (veh/h)	Dominant Lane Flow (veh/h)	Subdom. Lane Flow (veh/h)
Range	1.5-4.1	3.3-12.9	NA	0-2070*	90 - 1700*	90 - 1620*	90 - 1510*
Average	**2.52**	**4.88**	**0.52**				

* Rough value read from Figures 10 - 14 in the FHWA report *(3)*

Average values for	t_f	t_c	t_f / t_c
All data	**2.52**	**4.88**	**0.52**
Single lane: 1x1 ($n_c = n_e = 1$)	2.60	4.69	0.55
Two-lane: 2x2 ($n_c = n_e = 2$)	2.60	5.12	0.51

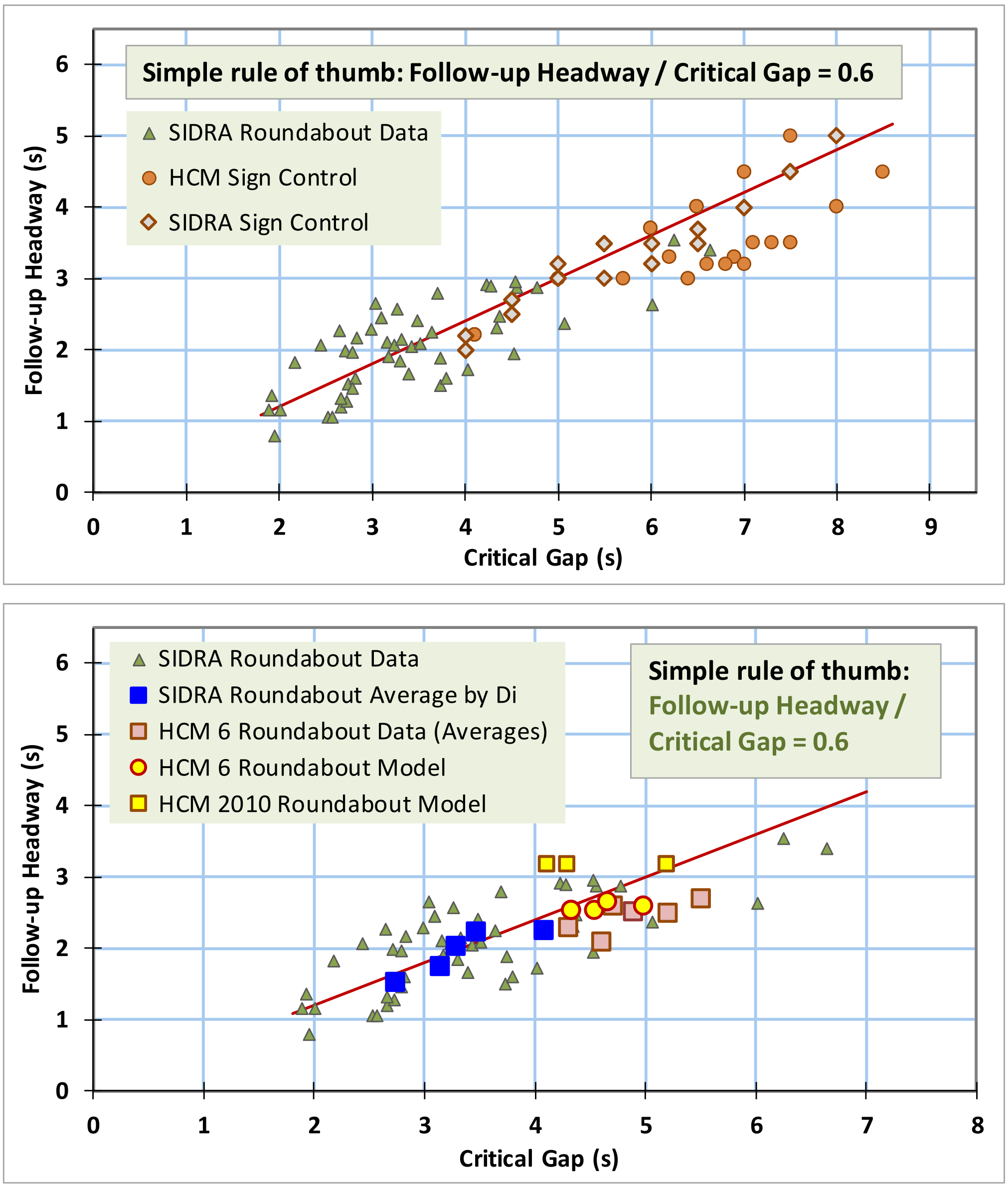

Figure 2 - The relationship between the follow-up headway and critical gap parameters for roundabouts and two-way sign control

Figure 2 shows the correlation between the two gap acceptance parameters for roundabouts including the HCM 6 and HCM 2010 model parameters given in *Table 1* and the Australian roundabout data summarised in *Table 2* as well as the default parameter values used for two-way sign control in SIDRA INTERSECTION. For the Australian data as the basis of the SIDRA Standard capacity model, average values categorized by Inscribed Diameter are also shown in *Figure 1* (values given in *Table 2*). While the SIDRA Standard model uses the Inscribed Diameter to calculate follow-up headway and critical gap parameters, the HCM 6 and HCM 2010 models use fixed values of these parameters. Refer to the FHWA Report SA-15-070, Chapter 4 for analyses of HCM 6 data in relation to this *(3)*.

Figure 2 as well as the parameter values shown in *Tables 1 to 3* confirm the simple rule of thumb in relation to the gap acceptance parameters which can be stated as "*the ratio of follow-up headway to critical gap is about 0.6*". Since both the follow-up headway and the critical gap parameters represent the behaviour of the same driver population, the strong correlation between these two gap acceptance parameters is not surprising.

MULTILANE ROUNDABOUT EXAMPLE

Examples comparing the HCM 2010, SIDRA Standard and other analytical roundabout capacity models for single-lane and multilane roundabouts were given in earlier papers *(5, 6, 10-15)*. In this paper, the multi-lane roundabout example shown in *Figure 3* is used to compare capacity estimates and the resulting degrees of saturation (v/c ratio), delay, LOS and queue length estimates from the *HCM 6*, *HCM 2010* and SIDRA Standard capacity models.

This roundabout example which has a mixture of one and two-lane entries and circulating roads is *Example Problem 2* given in HCM Edition 6, Chapter 33. The entry flows represent a fairly balanced origin-destination flow pattern. There are no pedestrian effects.

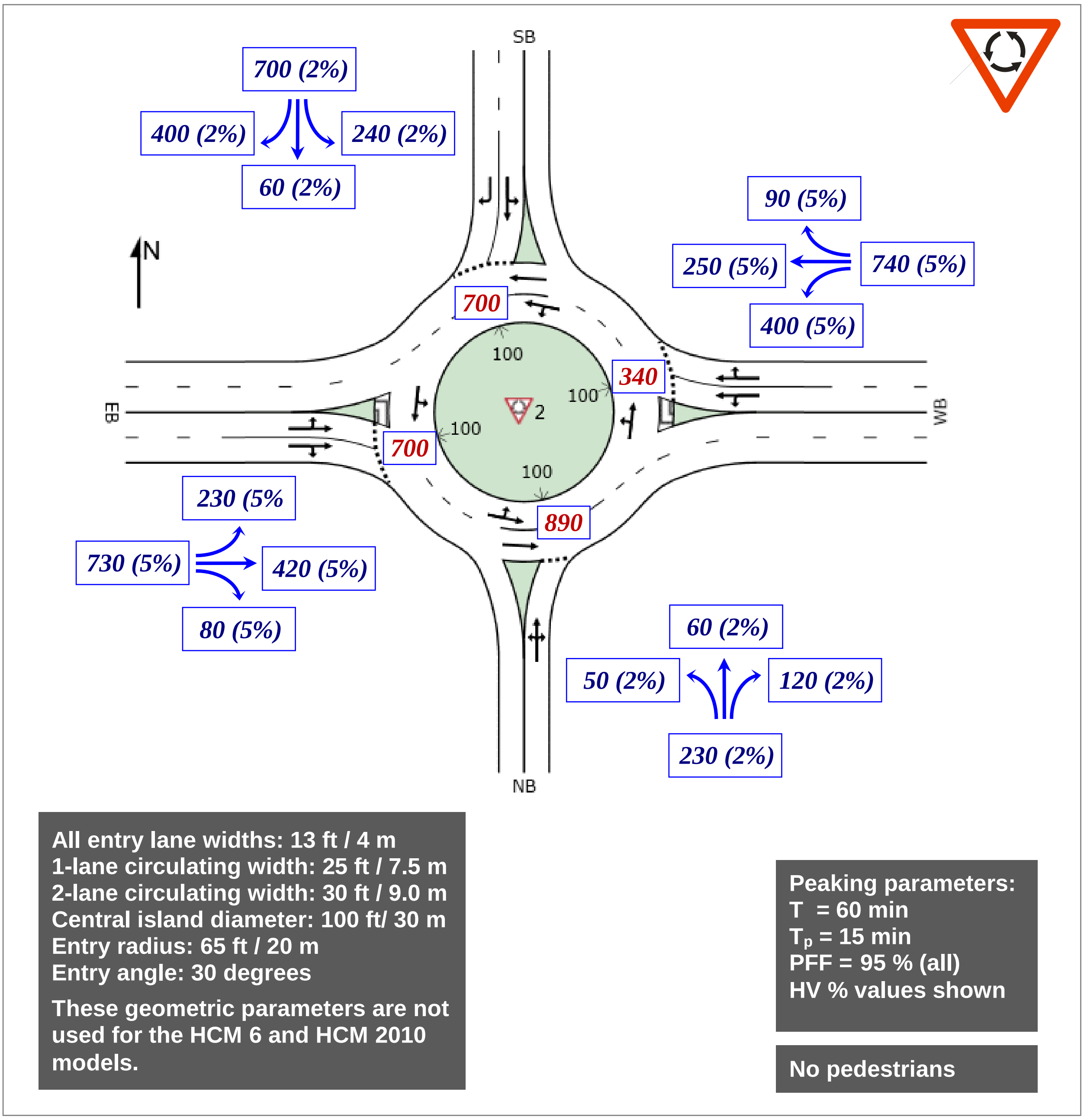

Figure 3 - Multilane four-way roundabout example (Example 2 in HCM 6, Chapter 33)

Analyses are carried out for a 15-min peak period. For the SIDRA Standard capacity model, the Environment Factor setting of **1.2** is used for the North (SB) approach which has two lanes on the approach and circulating roads (n_c = 2, n_e = 2) and **1.05** is used for all other approaches due to the mixed one-lane and two-lane arrangements for the approach and circulating roads (n_c = 2, n_e = 1 for South (NB), and n_c = 1, n_e = 2 for East (WB) and West (EB)).

The following model options are used for performance parameters for all models so that they are compared on the same basis:

- Delay Model: HCM Delay Formula,
- Roundabout LOS Method: SIDRA Roundabout LOS *(5)*, and
- General LOS method: Delay & v/c (HCM 6)

Although geometric parameters have been shown in both metric and US customary units, the latter system is used in the analysis reported in this paper. The parameter values in metric and US customary units are not precise converted values.

The heavy vehicle adjustment for entry lane traffic applies to the capacity directly in HCM 6 and HCM 2010 models as seen in *Equation (1)*. In the SIDRA Standard model, heavy vehicle adjustment for entry lane traffic applies to follow-up headway and critical gap values.

For the *HCM 6 and HCM 2010* models, Origin-Destination Factors or adjustment factors for Entry /Circulating Flow Ratio are not used. Geometric parameters other than number of lanes and lane disciplines are not relevant.

The results from the HCM 6, HCM 2010 and SIDRA Standard capacity models for this example are summarized in *Table 4*. In line with *Figure 1*, the HCM 2010 model estimates lower capacity and worse performance results.

The results indicate that *HCM 6* and the SIDRA Standard model calibrated using the Environment Factor parameter give close capacity and performance results although there are subtle differences between the two models. In particular, the SIDRA Standard capacity model estimates higher capacities for dominant lanes for the East (WB) and West (EB) approaches which have two lanes entering a single circulating lane (n_c = 1, n_e = 2). On the other hand, the HCM 6 and HCM 2010 models calculate equal entry lane capacities in the case of a single circulating lane. The SIDRA Standard model identified the Left lane as the dominant lane in the case of the WB (East) approach.

The SIDRA Standard model results would vary if the roundabout geometry parameters shown in *Figure 3* are modified. An analysis of the effects of more favorable and less favorable geometry parameter sets is given in an earlier paper *(5)*.

For all models, lane flows are determined according to the SIDRA INTERSECTION principle of equal degrees of saturation which assigns lower flow rates to lanes with lower capacity. On the North (SB) approach, unequal lane degrees of saturation apply due the *exclusive left-turn lane* (hence lane degrees of saturation cannot be balanced).

For the East (WB) approach, unequal lane degrees of saturation are identified by the HCM 6 and HCM 2010 models due to the high left turn volume which causes Lane 1 (Left lane) to act as a *defacto exclusive lane*. In the SIDRA Standard model, Lane 1 becomes the dominant lane on this approach, and a higher lane capacity is assigned to this lane as a result. As a result a small through flow is assigned to Lane 1 and the lane degrees of saturation are balanced.

The ability to identify defacto exclusive lanes as a function of lane capacities is an advantage of lane-based models. Approach-based models imply a balanced distribution of lane flows.

Table 3 also presents the circulating lane flows estimated by the SIDRA Standard model. The HCM 6 and HCM 2010 models use the total circulating flow rate only whereas the balance of circulating lane flow rates affects entry capacities in the SIDRA Standard model.

Table 4 - Comparison of capacity estimates for the HCM 6, HCM 2010 and SIDRA Standard models for the example shown in Figure 3

Approach	Entry Lane Flow		Capacity		Degree of Satn	Average Delay	Level of Service	95% Back of Queue
	Lane 1 (Left)	Lane 2 (Right)	Lane 1 (Left)	Lane 2 (Right)				
	(veh/h)		(veh/h)		(v/c ratio)	(s/veh)		(ft)
HCM 6 Roundabout Capacity Model								
NB (South)	242	na	607	na	0.40	11.8	B	43
WB (East)	421	358	964	964	0.44	8.3	A	57
SB (North)	316	421	650	722	0.58	14.0	B	86
EB (West)	384	384	675	675	0.57	15.0	B	84
HCM 2010 Roundabout Capacity Model								
NB (South)	242	na	559	na	0.43	13.4	B	37
WB (East)	421	358	742	742	0.57	12.9	B	87
SB (North)	316	421	621	645	0.65	16.8	B	80
EB (West)	384	384	501	501	0.77	30.9	C	135
SIDRA Standard Roundabout Capacity Model (Environment Factor = 1.05 & 1.2)								
NB (South)	242	na	599	na	0.41	12.1	B	55
WB (East)	425	354	1168*	971	0.36	7.1	A	68
SB (North)	316	421	648	713	0.59	14.2	B	102
EB (West)	335	434	678	878*	0.49	11.5	B	113

* Dominant lanes have higher capacity in the SIDRA Standard model whereas HCM models calculate equal entry lane capacities in the case of a single circulating lane. The SIDRA Standard model identified the Left lane as the dominant lane for the WB (East) approach.

Approach Flow and Circulating Flow Rates (SIDRA Standard Model Estimates)

Approach	Total Approach Flow (veh/h)	Circulating Flow Rate				
		Total	Lane 1 (Left)		Lane 2 (Right)	
		(pcu/h)	(pcu/h)	(percent)	(pcu/h)	(percent)
NB (South)	242	976	609	62%	367	38%
WB (East)	779	372	372	100%	na	na
SB (North)	737	772	500	65%	272	35%
EB (West)	768	764	764	100%	na	na

All results are obtained from the SIDRA INTERSECTION software.

Degree of saturation (v/c ratio) is the critical lane value (highest for any lane).

HCM Delay Formula and Roundabout LOS Method = *SIDRA Roundabout LOS* are used for all capacity models.

SIDRA Back of Queue formula is used for all capacity models (highest for any lane shown). Larger values for the SIDRA standard capacity model compared with the HCM 6 model is due to different lane flow rates.

O-D Factors in the SIDRA Standard model for this example were in the range 0.82 to 0.94 indicating fairly balanced conditions.

ANALYSIS OF FUTURE TRAFFIC CONDITIONS

As a result of lower capacities estimated by the HCM 2010 capacity model, there has been a considerable amount of discussion about the causes of lower roundabout capacities obtained under US traffic conditions. In particular, it has been discussed whether capacity of US roundabouts would increase over time with increased driver familiarity and increased driver aggressiveness due to higher demand and congestion levels at roundabouts in the future *(5, 19)*. The increases in the capacity estimates from the HCM 6 model compared with the HCM 2010 model could be considered in relation to this.

This subject is discussed in HCM Edition 6, Chapter 2 *(1)* which states that "*the capacities presented here are believed to be higher primarily due to the larger and more saturated dataset and not primarily due to an increase in capacity over time.*" and "*Although it has generally been assumed that roundabout capacity values in the United States will increase as drivers become more experienced with roundabouts, it has not been possible to provide direct evidence of this characteristic in the available data.*" The details of the related analysis can be found in the FHWA Report SA-15-070, Chapter 5 which shows that examination of data at two roundabouts observed under saturated conditions in both 2003 and 2012 revealed no significant change in observed capacities *(3)*. However, HCM edition 6, Chapter 2 has noted that roundabout capacity values in one city with a large number of roundabouts (Carmel, Indiana) are significantly higher than average for US conditions.

Nevertheless some practitioners believe that higher capacities should be applied in the analysis of future traffic as in the case of design life analysis. In view of this, Environment Factor values of **1.0** and **1.1** instead of (**1.05** and **1.2**) could be used for future traffic analysis in the SIDRA Standard model under the US HCM (Customary or Metric) software setup in the SIDRA INTERSECTION software. *Table 5* shows the results of a design life analysis with 2.5% uniform traffic growth over 10 years (all demand flows increased by 25 %) for the example in Figure 3 using these lower Environment Factor values in the SIDRA Standard model and comparing the results with the HCM 6 model.

An additional aspect of the SIDRA Standard model should be noted when analyzing future conditions with increased demand flows. The follow-up headway and critical gap values are reduced with increasing circulating flow rate (except the critical gap values for very high circulating flow rates) in the SIDRA Standard model as seen in *Figure 4*. The increased demand flows to represent future conditions in design life analysis mean increased circulating flow rates, and therefore reduced gap acceptance parameters. This effect, which is additional to the decreased Environment factor values, is in the results shown in *Table 5*.

There is no discussion in the HCM Edition 6 or the FHWA Report SA-15-070 about the dependence of gap acceptance parameters on circulating flow rates. Analysis of this using the HCM 6 data is recommended.

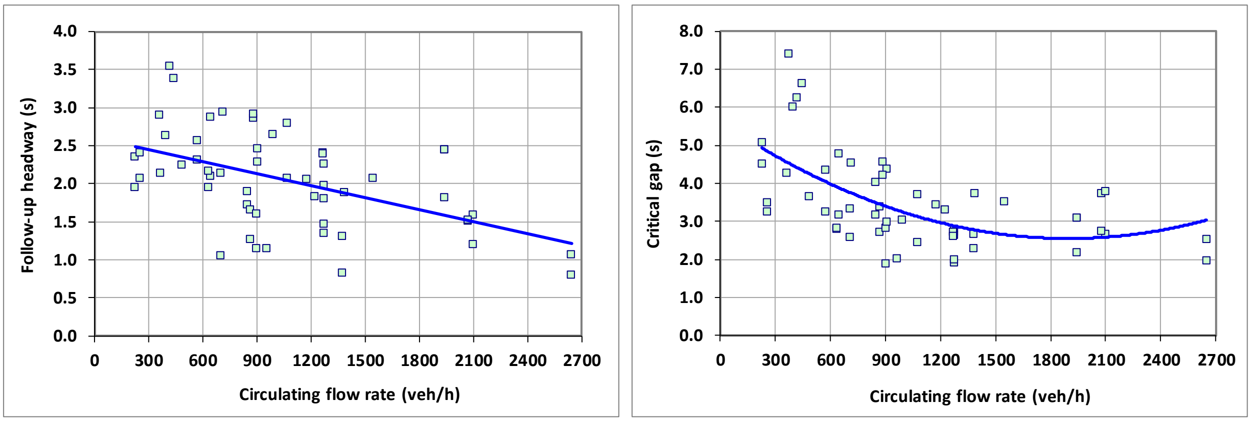

Figure 4 - Reduced follow-up headway and critical gap values with increased circulating flow rates

Table 5 - Comparison of capacity estimates for the HCM 6 and SIDRA Standard models with demand flows increased by 25 % for the example shown in Figure 3

Approach	Entry Lane Flow		Capacity		Degree of Satn	Average Delay	Level of Service	95% Back of Queue
	Lane 1 (Left)	Lane 2 (Right)	Lane 1 (Left)	Lane 2 (Right)				
	(veh/h)		(veh/h)		(v/c ratio)	(s/veh)		(ft)
HCM 6 Roundabout Capacity Model								
NB (South)	303	na	493	na	0.61	21.2	C	79
WB (East)	526	447	885	885	0.59	11.8	B	105
SB (North)	395	526	545	613	0.86	31.4	C	202
EB (West)	480	480	567	567	0.85	36.2	D	195
SIDRA Standard Roundabout Capacity Model (Environment Factor = 1.0 & 1.1)								
NB (South)	303	na	534	na	0.57	18.0	B	92
WB (East)	544	430	1147*	907	0.47	9.0	A	101
SB (North)	395	526	597	706	0.75	21.4	C	168
EB (West)	403	558	551	763*	0.73	17.6	C	286

ROUNDABOUT AS AN INTERACTIVE SYSTEM IN CAPACITY MODELING

HCM Edition 6, Chapter 2 states that "*... the capacity models in this chapter focus on one entry of a roundabout at a time. The roundabout is considered in its entirety only in the determination of conflicting flow for the entry under consideration.*" *(1)*. This means modeling roundabout capacity as a series of T intersections not as a system.

On the other hand, the SIDRA Standard capacity model treats a roundabout as a closed system with interactions among roundabout entries. This requires an *iterative* capacity estimation process that takes into account many parameters that are calculated as a function of the capacities estimated in the previous iteration, and in turn, affect the capacities in the current iteration.

While the traditional method of treating roundabout entries independently (other than determining total circulating flows) may be adequate for low to medium flow conditions, the treatment of a roundabout as an interactive system improves the prediction of capacities under heavy flow conditions, especially at *multi-lane roundabouts* with *unbalanced* demand flow patterns *(9-16)*.

The treatment of a roundabout as a closed system involves the following capacity model elements:

(i) ***Capacity constraint***: Circulating and exiting flow rates at the subject approach are affected by entry flow rates limited to the capacity flow rate when the demand flow rate exceeds the capacity (i.e. when some entry lanes are oversaturated) at upstream approaches. HCM Edition 6, Chapter 22 acknowledges this but it does not seem to be incorporated in the capacity procedure *(1)*.

(ii) ***Bunched headway distribution for the circulating flow***: Bunching in the circulating flow reflects the bunching of unqueued vehicles in the arrival flow (due to the effect of upstream signals) as well as the bunching that represents queued vehicles entering from upstream entry lanes of the roundabout. The *bunched headway distribution* of circulating road headways used in the SIDRA Standard model *(18, 19)* allows the effect of the number of circulating lanes and the lane balance of the circulating flow on the entry capacities. This headway distribution also allows the use of *extra bunching* to model the effect of upstream signalized intersections or pedestrian crossings on roundabout capacity. The HCM 6 / HCM 2010 exponential regression model with the same form as the *Siegloch* M1 gap-acceptance model *(1, 5)* belongs to the group of models that assume the simple exponential (random) distribution of headways with no bunching. This model cannot take any of these parameters into account.

(iii) ***Lane balance of circulating flow and entry flow rates***: This is affected by entry lane flow rates of contributing upstream entry flows (including the effect of approach lane underutilisation), and reflected in the *bunched headway distribution* of circulating road headways. In the SIDRA Standard model, entry lane capacities depend on the balance of circulating as well as approach lane flow rates. The models that use the total circulating flow rate only and assume random headway distributions cannot take into account the effect of the balance of circulating lane flow rates on capacity.

(iv) ***Unbalanced flow conditions***: Under these conditions, circulating flow in front of an approach originates mostly from one approach and is highly queued on the approach before entering the roundabout with uniform queue discharge headways, thus reducing the downstream entry capacities. These are the conditions which can be alleviated by the use of *roundabout metering signals* used to create gaps in the circulating stream in order to solve the problem of excessive queuing and delays at approaches affected by unbalanced flow conditions *(9-16)*. The SIDRA Standard model includes these conditions by allowance for the effects of *origin-destination pattern* of entry flows, *proportion queued* and any *unequal lane use* at entry lanes of upstream approaches. HCM Edition 6 Chapter 22 discusses the effect of origin-destination pattern of entry flows but the model presented in this chapter does not include modeling of unbalanced flow conditions.

The above capacity model elements affect each other, thus requiring an *iterative* capacity estimation process. Although having a simple model is attractive, it is desirable for a roundabout capacity model to deal with specific conditions using additional elements such those discussed above rather than relying on a regression method for general average conditions.

COMMENTARY ON HCM EDITION 6 CHAPTER 22

While the HCM 6 roundabout capacity model discussed in this paper has sound features incorporating *"a combination of simple, lane-based regression and gap-acceptance models"* HCM Edition 6 Chapter 22 recognizes limitations of the roundabout capacity model presented in the chapter stating that "*The procedures presented in this chapter cover many of the typical situations that a user may encounter in practice. However, there are sometimes applications for which alternative tools can produce a more accurate analysis*.".

Metering signals on roundabout approaches, pedestrian signals at roundabout crosswalks, adjacent signalized intersections or roundabouts, more than two entry lanes on an approach and flared (short) lanes are listed as conditions beyond the scope of the HCM model and suggested for treatment by alternative tools. The SIDRA INTERSECTION software includes direct analytical model extensions to the HCM model or allows the use of the SIDRA Standard model calibrated for US traffic conditions as discussed in some detail in a previous paper *(5)*. In addition to discussions in previous sections, various comments related to the HCM Edition 6 roundabout capacity model are presented below.

Roundabout Networks

HCM Edition 6 Chapter 22, Section 3 states ""*Some software implementations may include more than one model or employ extensions beyond the original fundamental research conducted within a particular country. Some deterministic models can model an entire network of intersections but generally assume no interaction effects between intersections, thus potentially limiting their application.*".

In recent years, the SIDRA INTERSECTION software was extended to include a lane-based analytical network model that includes *capacity constraint* (limiting departure flows from oversaturated upstream lanes to capacity flows, in a way similar to the roundabout entry lane capacity constraint) and *queue spillback* (capacity reductions of upstream intersection lanes as a function of lane blockage probabilities estimated for downstream intersection lanes where queue storage spaces are limited). These features have been discussed in detail in recent papers and presentations *(23-25)*. This network model can be used for analysis of roundabout corridors, signalized or unsignalised pedestrian crossings on roundabout approaches, effect of upstream signals on roundabout capacity, fully signalized roundabouts (including signals on circulating roads), and so on.

The effect of upstream signals on roundabout capacity is modeled using the *extra bunching* parameter. Theoretically, the Extra Bunching parameter does not affect gap-acceptance capacity in the case of random arrival distributions as it applies to the HCM 6 / HCM 2010 roundabout capacity model. However, the method is applied to these models by determining an *Extra Bunching Adjustment Factor* from capacities obtained with and without extra bunching using the bunched exponential model used in the SIDRA Standard capacity model.

Level of Service

HCM Edition 6 continues to use Level of Service (LOS) thresholds for roundabouts which are the same as those for *stop sign-controlled* intersections. The author remains of the opinion that this creates a bias against roundabouts when compared with signalized intersection treatments, and it is not appropriate for roundabouts because roundabouts are significantly easier to negotiate being subject to *yield (give-way) sign* control with only one conflicting (opposing) stream compared with *two-way stop sign* control with many conflicting streams. Slower opposing stream speeds, lower follow-up headway and critical gap values and higher capacities for roundabouts indicate that roundabouts are easier to negotiate than minor roads at intersections controlled by two-way stop signs (see *Figure 2*). For the example presented in this paper, the *SIDRA Roundabout LOS* method was used. This was discussed in detail in a previous paper *(5)*.

Model Categories

The author does not agree with the intersection model categorization as *Regression Models* and *Analytical Models* stated in the HCM Edition 6 Chapter 22 Section 2. These can be both considered as analytical models as opposed to microsimulation models. Similarly, categorization as *Deterministic Intersection Models* and *Stochastic Network Models* in Section 3 of Chapter 22 does not appear to be coherent especially because the latter seems to be associated with microsimulation models. Any categorization should recognize the stochastic elements of analytical models such as the fundamental overflow queue concept used in intersection performance functions and the probabilistic nature of queue spillback effects in networks.

Fuel Consumption and Emissions

The Highway Capacity Manual continues to exclude fuel consumption and emission modeling. This is a subject which is important for energy and environmental assessments of traffic operations and design. For detailed discussions on this subject, refer to papers by the author *(26)*.

CONCLUSION

It is hoped that discussions and recommendations in this paper will help towards a better understanding of the roundabout capacity model presented in the Highway Capacity Manual Editions 6 as well as contributing towards the development of future HCM and other roundabout capacity models.

Comparison of the results of microsimulation models with the HCM Edition 6 model and the SIDRA Standard model for the example presented in this paper is recommended.

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The author is the developer of the SIDRA INTERSECTION software. Comments presented in this paper regarding roundabout capacity models should be read with this in mind.

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